5. Cost and Emission Reduction Analysis of PFC Emissions from Aluminum Smelters in the United States

5.1 Introduction

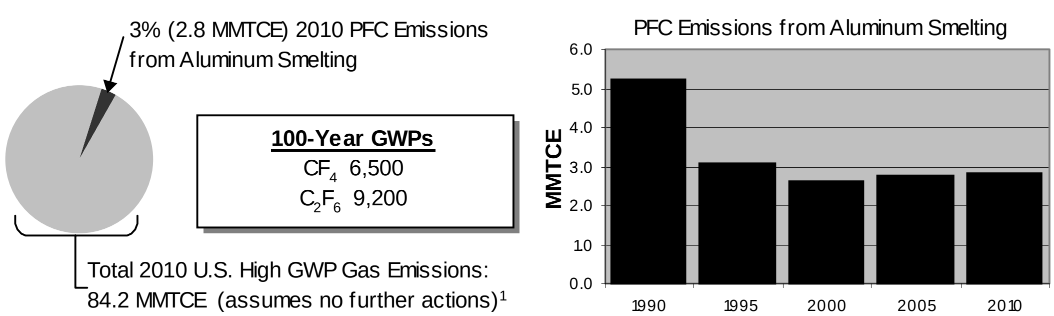
A major source of PFC emissions in the United States is primary aluminum production. Two perfluorocarbons (PFCs) are emitted as a byproduct of aluminum production. These PFCs—CF_4 and C_2F_6—have 100-year GWPs respectively of 6,500 and 9,200 times the warming potential of carbon dioxide. By 2010, the U.S. would be expected to emit 2.8 MMTCE of PFCs from aluminum production, assuming a business-as-usual scenario in which no further emission reductions are made after 1999 (see Exhibit 5.1).[1] However, as noted below, actual emissions are expected to be lower as a result of voluntary industry efforts in the future.

PFCs are formed as intermittent byproducts during the occurrence of anode effects (AEs). When the alumina ore content of the electrolytic bath falls below critical levels optimal for the aluminum-generating chemical reactions to take place, rapid voltage increases occur. These AEs reduce the efficiency of the aluminum production process, in addition to generating PFCs.

PFC mitigation technologies and practices vary in their availability, cost-effectiveness, and technical feasibility to reduce emissions. Computerized controls and point feeder systems, for example, while capital intensive to implement, are readily available. Other technologies, such as inert anodes, are decades away from potential implementation. In addition, some mitigation technologies may not be applicable to certain production systems, and certain smelters may require expensive retrofits to achieve significant reductions in PFC emissions.

In 1995, the U.S. EPA and 11 out of the nation's 12 primary aluminum companies, with the assistance of

Exhibit 5.1: U.S. Historical and Baseline PFC Emissions from Aluminum Smelting



[1] An explanation of the business-as-usual scenario under which baseline emissions are estimated appears in the Introduction to the Report.

The Aluminum Association, formed the Voluntary Aluminum Industrial Partnership (VAIP). The main goal of this partnership is to reduce PFC emissions while increasing the efficiency of aluminum production. The VAIP sets company-specific PFC emission reduction targets and includes periodic reporting of progress achieved toward those emission reduction goals. VAIP partner companies represented about 94 percent of U.S. production capacity as of 1999. While each company's emission reduction goal is tailored to site-specific conditions, the overall program goal is to reduce PFC emissions from VAIP Partners by 2.2 MMTCE below 1990 levels by the year 2000 (DOS, 1999).

To date, nine countries in addition to the United States have undertaken industry-government initiatives to reduce PFC emissions from primary aluminum production. All of these countries have achieved significant reductions in the rate of PFC emissions. More information on international PFC reduction efforts for each of these 10 countries is available in a document published by EPA in September 1999 (EPA, 1999).

5.2 Historical and Baseline PFC Emission Estimates

EPA estimates PFC emissions from U.S. aluminum manufacturing by summing the product of emission factors (*PFC kg/ton Al*) and activity factors (*tons Al*) for each producer. The historical estimated PFC emissions are reported in the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-1999 (EPA, 2001). EPA uses production data reported by VAIP partners. For manufacturers that do not report production, national production is apportioned based on smelter capacity of those for which data was not available. National production data and individual smelter capacity data from the U.S. Geological Survey (USGS) for the period 1990 to 1999 was used along with capacity data reported in the Aluminum Statistical Review for 1996 (The Aluminum Association, Inc., 1997).

The emissions are converted to million metric tons carbon equivalent (MMTCE) and summed to present the total PFC emissions for each year. The global warming potentials (GWPs) used in calculating MMTCE were 6,500 and 9,200 for CF_4 and C_2F_6, respectively. The equation used to estimate emissions is presented below.

$$Emissions = \sum_{smelters}((PFC\,kg / ton\ Al) * tons\ Al)$$

Emission factors for PFC per ton of aluminum are based upon the method found in IPCC/OECD/IEA 1999. The emission factors are estimated by measuring the relationship between smelter operating parameters, such as anode effect frequency and duration, and emissions. For those smelters that did not provide a complete data set required to estimate the process parameters, default parameters from the IPAI Survey (1996 edition) were used. The IPAI survey provides default values for the required parameters by technology type from 1990 to 1993 (IPAI, 1996). For subsequent years, the parameter data was kept constant at 1993 levels, as a conservative and simplifying assumption. Exhibit 5.2 shows historical PFC emissions from aluminum smelting for the years 1990 to 1999.

In order to evaluate the total cost to industry of reducing PFC emissions in 2010, the cost analyses have been conducted using a baseline that reflects emission reductions achieved by VAIP through 1999, but assumes that no additional emission reductions result from the CCAP programs after 1999. Exhibit 5.3 shows estimated baseline PFC emissions through 2010. This projection assumes that U.S. national aluminum production will fall over 110,000 metric tons in 2000, due to announced smelter closings resulting from high prices in wholesale electricity. For 2000 to 2005, production was predicted to grow at an annual rate of 1 percent; for 2005 to 2010, production was predicted to grow at 0.5 percent per year.

No future emission reductions are incorporated into these baseline projections; thus, emission factors are held constant at 1999 levels.

Exhibit 5.2: Historical U.S. PFC Emissions and Aluminum Production from Aluminum Smelting (1990-1999)

Type of Emissions	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
Emissions (MMTCE)										
CF_4	4.6	4.1	3.9	3.4	2.8	2.7	2.8	2.6	2.5	2.4
C_2F_6	0.7	0.6	0.6	0.5	0.4	0.3	0.3	0.3	0.3	0.3
TOTAL	**5.3**	**4.7**	**4.4**	**3.8**	**3.1**	**3.1**	**3.2**	**3.0**	**2.8**	**2.7**
Emissions (MT)										
CF_4	2,575	2,310	2,181	1,892	1,560	1,535	1,591	1,488	1,392	1,382
C_2F_6	274	239	226	181	145	138	138	127	117	116
Production (1000 MT)	**4,048**	**4,121**	**4,042**	**3,695**	**3,299**	**3,375**	**3,577**	**3,603**	**3,713**	**3,779**

Source: EPA, 2001.
Note: Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

Exhibit 5.3: Baseline U.S. PFC Emission Projections from Aluminum Smelting (2000 – 2010)

Type of Emissions	2000	2005	2010
Emissions (MMTCE)			
CF_4	2.4	2.5	2.6
C_2F_6	0.3	0.3	0.3
TOTAL (MMTCE)	**2.6**	**2.8**	**2.8**
Emissions (MT)			
CF_4	1,338	1,406	1,441
C_2F_6	107	112	115

Notes:
Forecast emissions are based on a business-as-usual scenario, assuming no further action.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.

5.3 PFC Emission Reduction Opportunities

During an anode effect, carbon from the anode and fluorine from the dissociated molten cryolite bath combine, producing CF_4 and C_2F_6. These gases are emitted from the exhaust ducting system or other pathways from the cell (e.g., the hood of the cell). In general, the magnitude of PFC emissions for a given level of aluminum production depends on the frequency of AEs (*# AE*) and duration of AEs (*AE duration*). This is shown in the following equations:

$$AE\ min/cell\text{-}day = \#\ AE * AE\ duration$$
$$PFC\ kg/ton\ Al = S * AE\ min/cell\text{-}day$$

$$Emissions = \sum_{smelters}((PFC kg / ton\ Al) * tons\ Al)$$

AE min/cell-day is the total duration (in minutes) of the total number of AEs per day in a given cell. The "S" in the second equation is a positive slope coefficient, specific to the smelter. The coefficient represents the relationship between the operating parameters (e.g., AE minutes and AE frequency) and PFC emissions, and is determined by measuring the composition of the smelter flue gas.

The frequency and duration of AEs depend primarily on the cell technology and operating procedures.

Emissions of CF_4 and C_2F_6, therefore, vary from one aluminum smelter to the next, depending on these parameters. As a result, to reduce PFC emissions each smelter must develop a strategy, which may include some or all of the following measures:

- ***Improving Alumina Feeding Techniques*** by installing point feeders and regulating feed with computer control. Point feeding consists of adding small amounts of alumina—about one kilogram—at various short intervals, usually less than one minute. This is the best alumina feeding method at present, and point feeding is now an important feature in all new cells, as well as in modernization or retrofitting projects for older cell lines.
- ***Using Improved Computer Controls*** to optimize cell performance. These systems monitor the different parameters that contribute to the build-up of AEs. System operators would be alerted before an AE can take place, thus reducing the AE frequency. Improved computer controls can also work in conjunction with point feeders.
- ***Training Cell Operators*** on methods and practices to minimize the frequency and duration of AEs. Also, operators can be trained to maintain strict control over alumina properties and cell operating parameters, and to provide timely and appropriate mechanical maintenance.

5.4 Cost Analysis

For this analysis, smelters in the United States were grouped by technology type (vertical stud Söderberg, horizontal stud Söderberg, sidework prebake, centerwork prebake, point feed prebake) and facilities within each technology type were assumed to upgrade in one of two ways:

- "minor upgrade," which includes only the implementation of improved computer controls; and
- "major upgrade," which includes an upgrade to point feed technology and improved computer controls.

The two upgrade options, as applied to the five smelter technology types, would imply ten separate cost and emission reduction options. However, communication with the VAIP Partners indicated that the majority of U.S. smelters have already implemented computer control technologies and further computer improvements will not significantly affect emissions for sidework prebake, centerwork prebake, and horizontal-stud Söderberg smelters. Also, minor and major upgrades for point feed prebake smelters were associated with minimal emission reductions. Therefore, only five upgrade and cost levels have been estimated: a minor upgrade for vertical stud Söderberg smelters and a major upgrade for vertical stud Söderberg, horizontal stud Söderberg, sidework prebake, and centerwork prebake smelters.

Capital costs were estimated for these five upgrade options using information from published sources (IEA, 2000), industry, vendors, and VAIP input. The net costs of an upgrade are calculated by comparing the initial capital investment and the incremental operating cost to the value of the resulting increase in aluminum production. For a minor upgrade at a vertical stud Söderberg smelter, the initial cost is approximately $4 million and operating costs are approximately $2 million per year, while the increase in production yields a benefit of over $2 million per year. Major upgrades are more expensive than minor upgrades, especially for facilities that use older smelter technologies, such as the vertical and horizontal stud Söderberg smelters. The initial investment for a major upgrade ranges between $60 and $65 million from Söderberg smelters and $8 to $9 million for prebake smelters. Incremental operating costs and the benefit of added production range from $1 to $3 million per year for all smelters.

To compare the relative costs and emission reductions for each upgrade option, two values were calculated. First, the cost per ton of emissions reduced was estimated. This "break-even" cost is the levelized annual cost divided by the amount of PFC emissions reduced. The levelized annual cost equals the net cost of the upgrade option divided by its respective lifetime; and the PFC emissions reduction equals the product of the technology-specific baseline emission factor, the anode effect reduction rate and the percentage of product capacity impacted by the change. The baseline emission factors were taken from published sources (IEA, 2000), and the reduction percentages were provided by the VAIP Partners (The Aluminum Association, Inc., 2001). The emission factors, along with the anode effect reduction percentages and production increases are shown in Exhibit 5.4. The final break-even costs are shown in Exhibit 5.5.

Exhibit 5.4: Baseline PFC Emission Factors and the Benefits of Upgrades

Option	Baseline PFC Emission Factor (TCE/ton Aluminum)	Anode Effect Frequency Reduction	Current Efficiency Increase*
Retrofit-Minor: VSS	1.05	16%	1.0%
Retrofit-Major: SWPB	0.53	50%	1.0%
Retrofit-Major: CWPB	0.27	41%	0.6%
Retrofit-Major: HSS	0.99	43%	0.4%
Retrofit-Major: VSS	1.05	26%	1.0%

Source: EPA estimates and The Aluminum Association, Inc. 2001.
Notes:
Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Soderberg, HSS = Horizontal Stud Soderberg.
*Current Efficiency is a measure of production output per unit electricity consumed. Increases in current efficiency provide an incremental increase in production. The increase in aluminum production is counted as a benefit and subtracted from the total cost of the upgrade.

Estimates of each upgrades' incremental emission reductions on a national level serve as the second set of calculated comparison values. The incremental reductions are equal to the product of the anode effect reduction percentages reported by the VAIP Partners (Exhibit 5.4), the estimated 1999 technology-specific emission rates, and the increase in production capacity that is estimated to result from each upgrade (Exhibit 5.6). The capacity eligible for each upgrade was provided by the VAIP Partners (The Aluminum Association, Inc., 2001); the percentage of the total capacity that experiences an upgrade was estimated by the EPA.

Exhibit 5.5 summarizes the incremental emission reductions and break-even costs associated with the five upgrade options. The costs of these upgrades range; computer controls are the least expensive, while conversions to point feed systems are more expensive, especially for Söderberg smelters. Overall, reductions of nearly 17 percent of 2010 emissions can be achieved at a maximum cost of $1 per metric ton of carbon equivalent, and reductions of over 30 percent of 2010 emissions can be achieved at a maximum cost of less than $10 per metric ton of carbon equivalent. Although it is unlikely that this scenario reflects the exact upgrade decisions that have been made in the past by each smelter, the total aggregate emission reductions under this scenario correspond to current estimates of emission reductions for the U.S. aluminum industry (The Aluminum Association, Inc., 2001).

It is also important to keep in mind that these cost estimates include only the reduction of PFCs. The technologies assessed also affect process CO_2 emissions and energy consumption (roughly 6.7 percent of the total CO_2 equivalent PFC emissions), which, if accounted for in this analysis, would result in lower costs per MTCE reduced.

Exhibit 5.5: Emission Reductions and Cost in 2010						
Option	Break-even Cost ($/TCE) Discount Rate		Incremental Reductions		Sum of Reductions	
	4%	8%	MMTCE	Percent	MMTCE	Percent
Retrofit-Minor: VSS	0.27	0.54	0.03	1.0%	0.03	1.0%
Retrofit-Major: SWPB	0.43	0.77	0.45	15.7%	0.47	16.7%
Retrofit-Major: CWPB	2.50	3.30	0.17	6.0%	0.65	22.7%
Retrofit-Major: HSS	5.23	6.82	0.14	5.0%	0.79	27.7%
Retrofit-Major: VSS	7.25	9.58	0.07	2.5%	0.86	30.2%

Notes:
Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Söderberg, HSS = Horizontal Stud Söderberg.
Conversion to MMTCE is based on the GWPs listed in the Introduction to the Report.
Sums might not add to total due to rounding.

Exhibit 5.6: Capacity Eligible and Capacity that Experiences Upgrades		
Option	Capacity Eligible (MT)	Percentage of Capacity that Experiences Upgrade
Retrofit-Minor: VSS	424,647	40%
Retrofit-Major: SWPB	279,000	100%
Retrofit-Major: CWPB	786,143	100%
Retrofit-Major: HSS	403,042	100%
Retrofit-Major: VSS	424,647	60%

Notes:
Technology types are as follows: PFPB = Point Feed Prebake, SWPB = Side Work Prebake, CWPB = Center Work Prebake, VSS = Vertical Stud Soderberg, HSS = Horizontal Stud Soderberg.

5.4 References

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